Photocurrents in topological materials

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When mentioning new materials for IR harversting, topological insulators [1] immediately come to mind. Their mid-gap surface states exhibiting spin-momentum locking raised hopes that surface photocurrents could easily be produce by irradiation with circularly-polarized light. However, the photocurrents produced in response to sub-bandgap light were shown to be remarkably minute, even when a high-intensity laser is considered [2].

In Ref. [3] we show that by adding a magnetic coating with a spatially periodic magnetic texture, the TI produces a significant surface photocurrent in response to circularly polarized light in the IR regime. This effect should, in principle, allow making diode-free IR sensitive photocells from topological insulator films. We discuss application of the effect to room temperature infra-red detection, and show that it can lead to a detector operating at much larger wavelengths then those available with existing technologies.

The device we propose and analyze consists of a bulk three dimensional topological insulator, whose surface is coated with stripes of magnetic material, see Fig. 1. We consider magnetic stripes which are evenly spaced. The stripes provide a spatially periodic magnetic Zeeman field, and their spacing defines a wave vector $\mathbf{q}$ along the plane. Via their magnetic coupling to the electrons in the surface state of the TI, the magnetic stripes break symmetries which suppress the photocurrents in their absence. Thereby, the magnetic stripes dramatically enhance the photocurrent response of the TI's surface. For the minimal model of the TI surface, the direction of the stripes' magnetization needs to have non-zero components both normal to the surface as well as along the vector $\mathbf{q}$. Photocurrents will flow parallel to the direction of the stripes (perpendicular to $\mathbf{q}$).

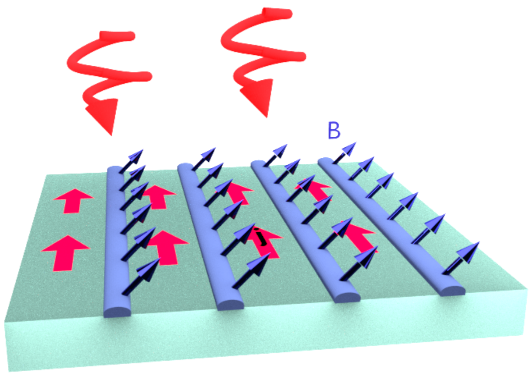

Figure 1: Proposed scheme for achieving a photovoltaic effect on a topological-insulator surface, coated by a magnetic grating. When the magnetization (depicted by blue arrows) breaks both rotation and reflection symmetries, circularly polarized light induces a photocurrent (red) in the direction parallel to the stripes.

The photocurrent response of the device can be described by a dimensionless, frequency dependent response function $\eta(\omega)$.For a continuous spectrum with intensity per unit angular frequency, containing both circular polarizations, we write $I(\omega)d\omega = 2\epsilon_0 c|\mathbf{E}(\omega)|^2$. The total current response is then:

$$j_y = \frac{e^3 v_F^2 q\tau}{2\epsilon_0 c\hbar^2}\int_0^{\Omega}\frac{I(\omega)}{\omega^2}\eta(\omega)d\omega, \tag{1}$$

where Ω is the high-frequency cutoff. Fig. 2 demonstrates a key feature of $\eta(\omega)$: it exhibits a strong maximum at frequency $\omega \approx 1.7 v_F|\mathbf{q}|$, where v_F is the velocity associated the Dirac cone. This result has significant implications in future applications of the proposed device: the frequency corresponding to the peak sensitivity of the device can be tuned by appropriately choosing the spacing of the magnetic stripes. We analyze the performance of this set-up at finite temperature and with the chemical potential tuned away from the Dirac point. This analysis gives an "operational" region for the device: we show that the performance of the device is not significantly reduced for temperatures and deviations of the chemical potential from the Dirac point up to $\hbar v_F|\mathbf{q}|$, which could translate to $300K$ in practical realizations.

We estimate that the two dimensional photocurrent density resulting from illumination with sunlight could reach $10^{-8}\frac{A}{m}$. Illumination with a conventional laser beam can yield currents of the order of $10^{-4}\frac{A}{m}$. A particularly appealing application of the device is room temperature detection of infra-red radiation. We explore the potential of this system to detect black-body radiation emitted at a variety of different source temperatures. We conclude that the device may be able to detect black-body radiation of objects at room temperature while itself being at a comparable temperature. Finally, we explore several theoretical figures of merit for the device as a room temperature IR detector. In particular we calculate the device's external quantum efficiency and its specific detectivity, which gives its normalized signal to noise ratio [4] . Near room temperature and with peak sensitivity tuned to wavelengths near $15\mu m$ we estimate a quantum efficiency of 0.01% and a specific detectivity

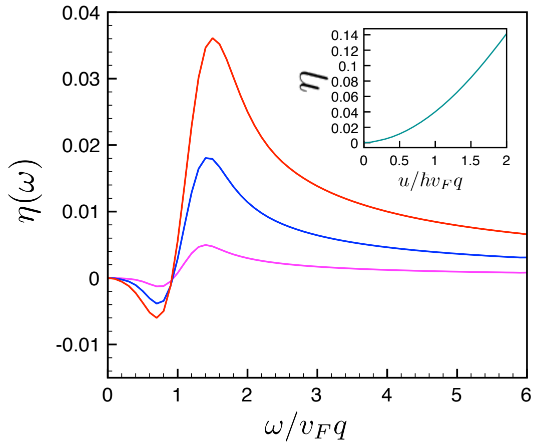

Figure 2: The dimensionless response function $\eta(\omega)$, for $u_x/\hbar v_F q = u_z/\hbar v_F q = 0.1, 0.2, 0.3$ (purple, blue and red, respectively). The horizontal axis gives the frequency ω in units of $v_F q$. The inset shows the saturation value η of the response function at high frequencies $\omega \gg v_F q$, as a function of $u/\hbar v_F q$, with $u = u_x = u_z$.

$\sim 10^7$ cm$\sqrt{\text{Hz}}$/W, *before* any device optimization takes place. Such a detectivity compares well with the detectivity of current room temperature photo-detectors, which can usually only detect up to 10μm. Importantly, the proposed device has the potential to be functional for wavelengths greater than 15μm. Our findings therefore support the idea that this set-up may be promising for room temperature detection of long wavelength infrared radiation.

In Ref. [5] we show that Weyl semimetals can generically develop photocurrents without the need of external couplings. Weyl spectrum is the 3D generalizations of the Dirac cone and thereby shares the same advantage of long-wavelength photon absorptions. Unlike Dirac systems, Weyl semimetals necessarily break either time-reversal (TR) symmetry or spatial inversion (I) symmetry, or both. The photocurrent response of a Weyl system differs from the Dirac counterpart in two crucial ways. First, Weyl cones have definite chiralities and always come in a pairs. They can be regarded as topological monopoles or antimonopoles of the Berry curvature. For an upright Weyl cone [Fig. 3(b)], the absorption of a circularly polarized photon flips the spin, resulting in asymmetric excitations along the drive direction. Yet, the direction of the photocurrent is governed by the chirality and hence, the sum of photocurrents from a Weyl node pair has to vanish identically. On the other hand, a Weyl cone can be tilted [6, 7] because of reduced symmetries. The corresponding photoexcitation is highly asymmetric about the nodal point [Fig. 3(c)]. The consequential photocurrent is controlled by the tilt and the chirality and there is generally no offset between photocurrents unless additional symmetries are imposed.

We contrast the performance of our effect with other

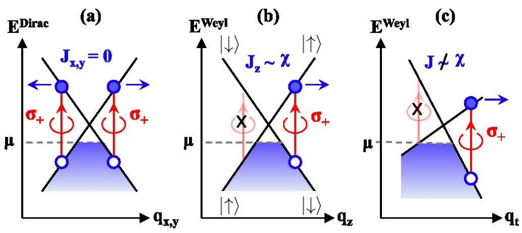

Figure 3: Schematics of photocurrent generations in Dirac and Weyl systems. Circularly polarized photons propagating along the z axis induce spin-flip vertical transitions denoted by the red arrows. (a) In an ideal 2D Dirac system, the excitations are symmetric about the node and thus the photocurrent vanishes. (b) In a 3D Weyl system with an upright crossing spectrum, the extra dimension allows an asymmetric particle-hole excitation along qz and creates a chirality-dependent photocurrent from each Weyl cone. However, the chiral currents from a monopole and an antimonopole negate each other, yielding no net current. (c) In the presence of tilt along some direction qt , asymmetric excitations can happen when the system is doped away from the neutrality. The resultant photocurrent is not just determined by the node chirality and the total current is generically nonzero.

photodetectors based on gapless semiconductors using the external quantum efficiency η_Q, defined as the ratio of the number of charge carriers to the number of incident photons. For a Weyl semimetal with $L_z = 100$ nm and a lateral dimension of a few m, $\eta_Q = \hbar\omega|J|Lz/(eILx)$ for mid-infrared frequency ($\sim 0.1eV$) at room temperature. In comparison, graphene grown on substrates designed to break I symmetry has been under study as a photodetector. The corresponding substrates introduce a strong disorder scattering and the existing and optimized photodetector has a very low $\eta_Q \sim 10^{-15}$ [8].

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